Cassini Navigation during Solar Conjunctions
via Removal of Solar Plasma Noise

P. Tortora[*], L. Iess

Dipartimento di Ingegneria Aerospaziale ed Astronautica,

Università di Roma "la Sapienza", Via Eudossiana 18, 00184 – Rome, Italy

Tel. +39-06-57174422, Fax. +39-06-44585670

Email: p.tortora@uniroma1.it, iess@hermes.ing.uniroma1.it

J.J. Bordi, J.E. Ekelund, D. Roth

Jet Propulsion Laboratory, California Institute of Technology

Navigation and Mission Design Section

4800 Oak Grove Drive, Pasadena, CA 91109 – USA

Tel. (818) 393-0613, Fax. (818) 393-4215

Email: John.Bordi@jpl.nasa.gov, jee@kepler.jpl.nasa.gov, Duane.Roth@jpl.nasa.gov

* Point of Contact

Abstract

Current deep space navigation systems rely on X-band radiolinks, used for both range and range-rate measurements. The attainable frequency stability (measured by the Allan deviation) generally is in the range 10^{-13}-10^{-12} over 10^3s, which broadly reflects in a range rate accuracy of about 10^{-3}-10^{-2} cm/s. Moreover, for missions in the ecliptic plane, a critical phase is represented by the solar conjunctions which, depending on the spacecraft trajectory, can last up to two weeks, with measurement errors exceeding 1 mm/s. The dramatic decay in the attainable navigation accuracy is caused by the phase scintillation due to the solar plasma. As a matter of fact, in the orbit determination process, radio data collected when the line of sight falls within 40 solar radii form the Sun are usually discarded, leading to long time spans during which navigation cannot rely on actual data. For the Cassini spacecraft, currently in cruise flight to Saturn, 30 days of data across the 2000 and 2001 solar conjunctions were removed for navigation purposes. While this strategy is widely acceptable and proven during the cruise flight, it is not recommended during critical mission phases, when frequent ground-commanded maneuvers are executed.

The Cassini tour of the Saturn system will begin with the Saturn Orbit Insertion (SOI) maneuver, scheduled on July 1st 2004, a few days before a solar conjunction. A significant improvement of the navigation accuracy would be achieved using, in the orbit determination process, *all* radio data collected up (and past) SOI.

The Cassini spacecraft and ground segment are currently used to test a novel RF *multilink* technology to perform radio science experiments (RSE). The on-board configuration is based on a X/X transponder, which generates a reference signal to the Ka-Band Exciter (KEX) for the X/Ka link; furthermore a coherent frequency translator (KaT) is used for a Ka/Ka link. The primary goals of RSE are the measurement of the solar gravitational deflection during the Solar Conjunction Experiments (SCE), and the search for gravitational waves (due for example to the coalescence of massive black hole binaries) during solar oppositions.

During the SCE, the estimation accuracy of the post-Newtonian parameter γ will be strongly enhanced by the plasma calibration, thanks to the multifrequency link. With this method, the sky frequencies, reconstructed using data from a wideband open loop receiver (OL) in the three bands (X/X, X/Ka, Ka/Ka), are coherently combined to remove the effects

of the solar plasma, the major noise source in the Doppler observable.

The analysis of the 2001 Cassini solar conjunction data, using the multifrequency plasma calibration scheme, has shown an improvement of a factor of 10 over the noise of the bare Ka/Ka observable and a factor of 100 over X/X data. At an impact parameter of about 25 solar radii, the Allan deviation is as low as 2.10^{-14} at integration times of 1000 s, corresponding to a one-way range rate accuracy of about 0.003 mm/s. As the calibrated frequency residuals exhibit a nearly white power spectrum over a broad frequency range, at 10s integration time the accuracy is degraded by a factor of 10. At an impact parameter of about 6 solar radii, the Allan deviation is on the order of 4.10^{-14} (1000 s integration time), still well below the corresponding uncalibrated X and Ka bands values. Further processing, including the use of the available advanced media calibration data (obtained from water vapor radiometers and microwave temperature profilers developed for the Cassini radio science experiments) may lead to even better results.

The multifrequency link, originally devised for radio science experiments, can provide also a very significant improvement in the navigation accuracy, especially during solar conjunctions. The Doppler observables used by the Orbit Determination Program (ODP) are however obtained from different receivers (BVR), which digitally lock and track the carrier in a closed loop (CL).

In this paper the steps required to compute a "plasma free" observable are described and discussed in detail. First, the algorithm to reconstruct the sky frequencies from wideband OL data is illustrated and, using a simple model of the orbital dynamics, the obtained residuals are characterized in terms of Allan deviations and power spectra. We then show how the plasma calibration scheme, used to generate plasma free observable for each band, leads to a much improved signal stability and to a reduced spectral density.

A thorough comparison among the Doppler frequency residuals has been performed using, in the ODP, the raw and calibrated OL and CL sky frequencies reconstructed from the June-July 2002 Cassini solar conjunction data. Figures 1 and 2 show respectively the raw (uncalibrated) and plasma-calibrated X-band frequency residuals, at 5 minutes compression, in the time interval between June 9th and July 5th 2002. The rms value of the Doppler residuals is reduced from about 1.5 mm/s for the uncalibrated data to about 7.5E-3 mm/s for the plasma calibrated data.

Since the rms value of the Doppler residuals is usually used to *weight* the data in the

orbit determination process (namely for the estimation of the updated spacecraft state), the advantage of obtaining small rms values is easily recognized. Actually, when the updated orbital solution is mapped to some reference point of the spacecraft trajectory, the ellipsoid of uncertainty in the spacecraft position is largely determined by the weight given to the observables, and by the uncertainties in the spacecraft dynamics (thruster gas leaks and other non-gravitational accelerations are two examples). Thus, assigning the weight of the observables according to their improved rms value leads to a more precise determination of the spacecraft position.

During the June-July 2002 solar conjunction experiment, for the first time, the plasma calibration procedure has been applied to CL navigation data, showing excellent results. OL and CL sky-frequencies agree within 40 mHz rms when the S/C has an impact parameter larger then 10 solar radii, while they are significantly different (up to 300 mHz rms) beyond this limit. This difference is probably due to the greater flexibility of the OL receivers, which allow to adjust the phase locked loop parameters in the digital processing of the data. At small impact parameters, when plasma scintillation becomes larger, OL sky-frequencies must therefore be preferred to generate the plasma-free Doppler observable. The analysis of the data collected during the 2002 solar conjunction of the Cassini spacecraft clearly shows that the use of a multifrequency link provides range rate measurements whose accuracy is virtually independent of the solar elongation angle.
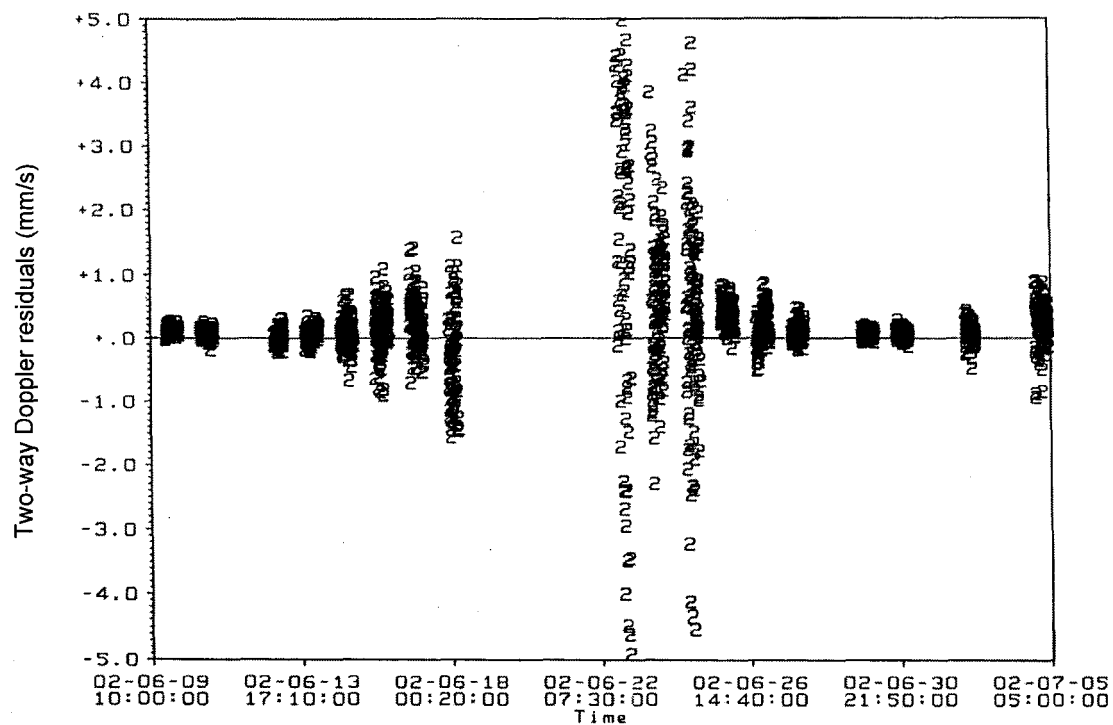
**Figure 2: Uncalibrated X-band frequency residuals
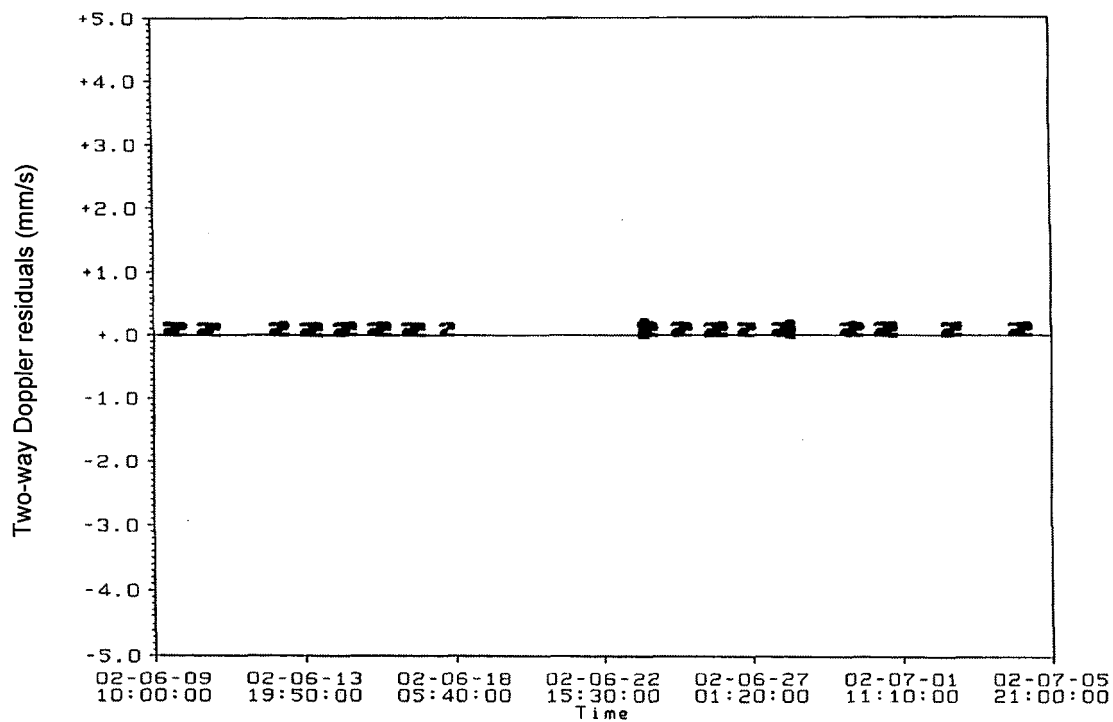during June-July 2002 Cassini solar conjunction**

**Figure 2: Plasma calibrated X-band frequency residuals
during June-July 2002 Cassini solar conjunction**

Condensed abstract

The Cassini spacecraft and its ground segment are currently used to test a novel RF *multilink* technology to perform radio science experiments. During solar conjunctions, this allows the complete removal of the solar plasma noise from the navigation observables, coherently combining the signals received in the three bands X/X, X/Ka and Ka/Ka. On June-July 2002 a Cassini solar conjunction occurred, and this procedure was tested for the first time. We show that, using the multifrequency plasma calibration scheme, the rms value of the frequency residuals is reduced of a factor of 200 over the uncalibrated data.